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CATASTROPHE ON THE HORIZON:
A SCENARIO-BASED FUTURE EFFECT OF ORBITAL SPACE DEBRIS

By

Jack Donahue, Major, USAF

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Instructor: Dr. John T. Ackerman

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Section 1 – Introduction

Orbital Space Debris Defined

Orbital space debris can be defined as dead satellites, discarded rocket parts, or simply flecks of paint or other small objects orbiting the earth. It is simply space "junk," but junk that can be extremely dangerous to space assets. Most of the debris concerns are associated with satellites and manned space missions in Low-Earth orbit (LEO). LEO extends out to about 5,000 kilometers from the earth's equator.[1] There are two other bands of orbits that contain satellites. The first, Geosynchronous-Earth orbit (GEO) is the outer most band and extends out to approximately 35,888 kilometers. The second is the Medium-Earth (MEO) orbit which is located between LEO and GEO in the approximate range of 10,000 to 20,000 kilometers. Typically, satellites in GEO and MEO are shielded (hardened) from harmful effects of space such as radiation and are more resilient.[2] However, there are roughly 300,000 small objects (chips of metal or specks of paint) that are too small to be tracked (merely four millimeters in size), but large enough to do potential harm to any object they would strike given the enormous speeds of collision implied by orbiting objects.[3] Nevertheless, the current debris population in the LEO region has reached the point where the environment is unstable and collisions are becoming the most dominant debris-generating mechanism (See Table 1). [4] Of the nearly 100,000 pieces of debris larger than a marble in orbit; those at altitudes above 1,000 kilometers will remain in orbit for centuries, and those above 1,500 kilometers for millennia.[5] Currently, there are approximately 900 active satellites in Earth orbit and roughly 10,000 pieces of space debris longer than 5 inches traveling at approximately 11,000 miles per hour (See Figure 1).[6] Even a small piece of debris that is less than ½ inch is capable of doing serious damage, like depressurizing a spacecraft (exposing crew to decompression sickness from lowering of

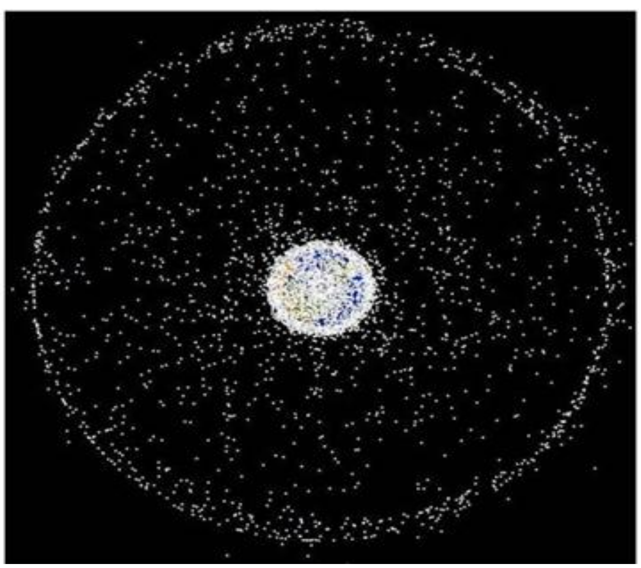
environmental pressure).[7] Each time a launch into space occurs it can potentially create more space debris from pieces of the rocket or from the satellite itself being put into orbit. If any of these pieces were to come into contact with an active space asset, it could not only be catastrophic for the asset, but result in adversely affecting television, cell phones, GPS signals, national security, intelligence (reconnaissance and imaging), and weather forecasting.

Orbital debris source	Size range	How observed	Primary instrument (United States)	Estimated number on-orbit (2006AD)
Payloads and rocket bodies past end-of-life	>5 cm	Tracked and cataloged	SSN radars	3600
Mission-related	<1 m	Tracked and cataloged	SSN radars	1270
Fragments of on-orbit explosions and collisions	<1 m	Tracked and cataloged, <10 cm observed statistically	SSN radars, Haystack and HAX radars	>1 000 000
Sodium potassium coolant droplets	~1–5 cm	Observed statistically	Haystack and HAX radars	~55 000
Solid rocket motor char, slag, and dust	~100–5 cm	Observed statistically	Returned surfaces[a], ground-based tests	Unknown
Ejecta and paint flakes (degradation products)	<1 mm	Observed statistically	Returned surfaces[a]	Unknown
Meteoroids	<1 cm	Observed statistically	Returned surfaces[a], ground-based optical and radar measurements	Unknown

[a]Space shuttle, ISS module, HST solar panels, Eureka, and LDEF surfaces

Source: *Journal of Aerospace Engineering*, Dec 2007, Vol. 221, Issue 6.

Table 1. LEO Space Debris Source Size Ranges



Source: *Astronomy & Astrophysics Review*, Jan2007, Vol. 14 Issue 1.

Figure 1. Snapshot View of the About 9,000 'Large' Objects With Known Orbits

Research Questions

The main question of this research is: *Should the United States have an increased concern about orbital space debris?* The supporting question is: *If so, what futures could result from the driving forces and effects of this debris?*

Research Thesis

Space debris continues to accumulate each and every year. This trend should be alarming. Therefore, the thesis of this research paper is: *If the United States does not resolve the orbital space debris problem, it will lead to a catastrophic collision between debris and satellites or manned spaceflight missions that will in-turn adversely impact global communications, the economy, safety (danger to space crew) , or US national security.*

Research Purpose

The purpose of this research is to bring some much needed attention to the growing problem of space debris and to understand the driving forces behind the orbital space debris problem. An examination into the effects debris may have in the future will shed some light on the situation and put into perspective how serious this issue has become and what impact it could have on our society and the world. This research is intended to identify some potential futures as a result from orbital debris and highlight potential solutions for consideration. Hopefully this will spark some debate, so policy or legislative changes can be considered within our government in order to avoid a potential space catastrophe in the near future.

Section 2 – Background Information

Current Situation Examined

Today, spacecraft follow a carefully synchronized orbit using signals from ground controllers, who track known objects, to avoid the debris.[8] Therefore, countless man hours and millions of dollars are spent cataloging space debris in order to prevent disastrous collisions with US space assets. Space operators do this by getting a rough fix on the trajectory of debris and craft from the US Air Force (US Space Surveillance Network (SSN), managed by US Strategic Command), which provides radar data on spacecraft trajectories.[9] As the amount of orbital debris continues to rise, operators are finding it increasingly difficult to keep tabs on all the objects.

Previous Space Debris Incidences

Monitoring objects in space is only part of the answer. The sheer volume of space debris will soon make it difficult to maneuver spacecraft without risking an accident.[10] In fact, there have already been numerous logged incidences with orbital debris (See Table 2). In 1983, for example, a paint speck only 0.2 millimeters in diameter made a 4 millimeter dent in the Challenger space shuttle's windshield.[11] In September 1991, a space shuttle mission was interrupted to allow the shuttle Discovery to avoid debris from a decaying Soviet-era satellite.[12] In July 1996, the first recorded orbital collision occurred between a discarded rocket stage and a French spy satellite damaging the satellite's stabilization system sending it tumbling, although it was able to recover.[13] On March 12, 2009, debris came alarmingly close to the International Space Station (ISS), forcing crew members to take refuge inside a Russian-built Soyuz lifeboat.[14] Studies have shown that operational spacecraft have small collision activity (one object colliding with another object) that increases over time as the small fragment population increases and

could prove to be mission-ending for the spacecraft.[15] Without the United States taking steps to remove orbital debris, the risks of collisions resulting in the destruction of spacecraft could create clouds of new debris objects compounding the problem and raising the probability of new collisions.[16]

Launched	Spacecraft/Event detail	Occurred
12-August-62	ECHO collision with own final stage after 1 orbit. Dent in balloon created strange signal return profile	12-August-62
28-November-64	Mariner 4 hit by meteoroid – minor damage to thermal insulation	
21-December-72	Sfera (9) hit by space debris/meteoroid. Part of the spacecraft large enough to be tracked broke off and re-entered	21-April-02
05-September-77	Voyager 1 scan platform initially jammed by debris. Residue from manufacturing process. Later cleared	23-February-79
14-July-78	ESA GEOS 2 solar cell short-circuit, possibly due to debris collision. Three of seven experiments adversely affected	14-August-78
26-April-80	Navstar 6 hit by space debris. Lost one month of life	01-July-87
21-February-81	Japan solar observation satellite Astro A (Hinotori): sun shade damaged by Perseid meteors	15-June-91
28-March-83	NOAA 8 entered safe mode. Battery 1 had no working regulator – overcharged and exploded 5 h later	30-December-85
18-June-83	STS 7 windshield damaged in-orbit by 'Flek of paint' impact	20-June-83
23-May-85	Yantar-4K2 (16) exploded in orbit	21-June-85
20-February-87	GEO-IK (9) exploded. Hundreds of trackable pieces of debris	17-December-87
12-July-89	Yantar-4K2 (48) spy satellite automatically exploded for security/safety reasons	26-July-89
18-November-89	COBE appeared to shed debris (possibly insulation)	15-June-93
24-April-90	Hubble Space Telescope Space Debris damage to aft shroud	11-February-97
01-December-90	DMSP 5D-2 F10 solid motor explosion (50 fragments in-orbit)	01-December-90
10-March-94	SEDS II tether snapped by meteorite (June 1994)	15-June-94
07-July-95	CERISE collided with spent 1986 Ariane stage 6-metre stabilizing boom vapourized	24-July-96
06-April-97	Progress-M 34 collided with Mir 'Spektr' module, damaging its Solar Array, and puncturing Spektr	25-June-97
15-February-99	Telstar 6 three hour outage, possibly space debris impact	11-April-02
23-February-99	Sunsat lost - possible debris strike	19-January-01
26-December-99	EORSAT (47) COSMOS 2367 break-up post EOL, 300+ debris. 40% in ISS crossing orbits	21-November-01
03-July-02	CONTOUR Star 30B solid motor failed, possibly exploded, during 50s. burn to leave Earth orbit	15-August-02
15-July-04	Meteosat-8 (MSG) unexpected spin-rate change and orbit change attributed to collision with space debris	unknown
15-April-05	Aura (EOS) HIRDLS IR viewing mirror blocked by debris – kapton insulation blanket	unknown
28-August-02	DART collided with target spacecraft MUBLECOM during 'auto' rendezvous test	22-May-07

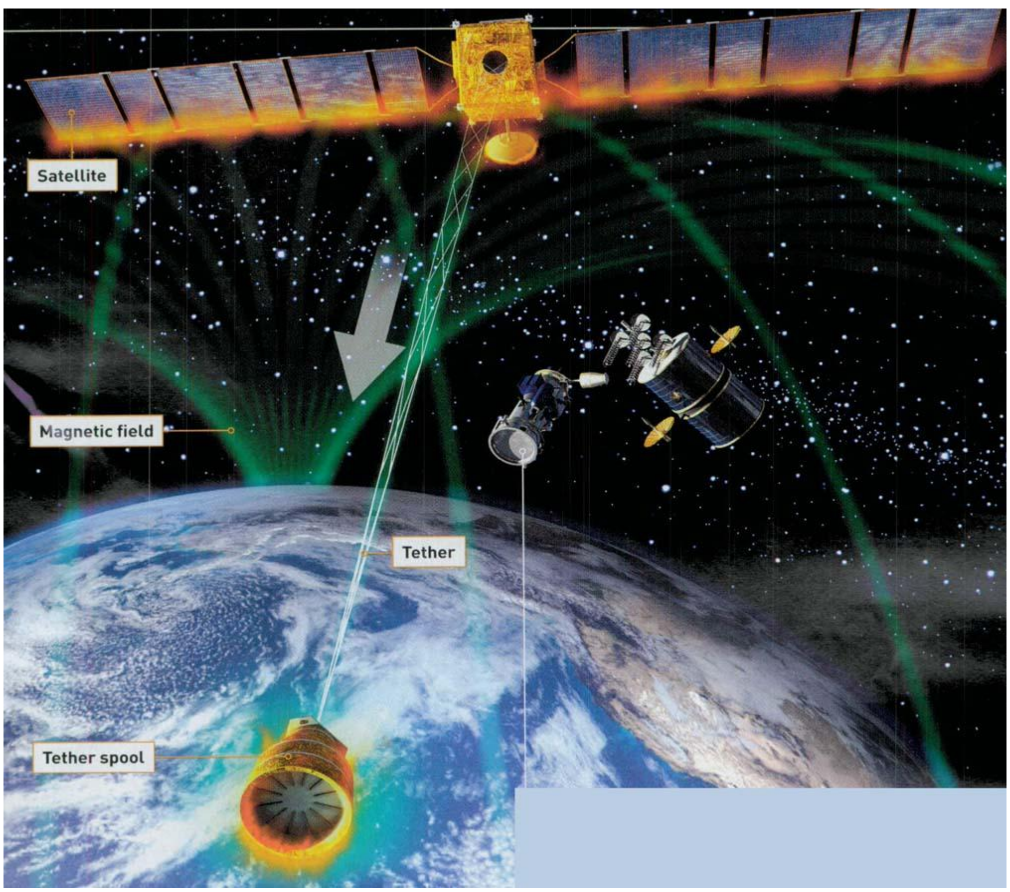
Source: *Journal of Aerospace Engineering*, Dec 2007, Vol. 221 Issue 6.

Table 2. Examples of Debris Hits on Spacecraft

Reducing and Clearing Orbital Debris

Scientists and space agencies around the world have been working hard to come up with several ideas for clearing orbital debris. One of these ideas is to use robotic trash collectors that shove large pieces of junk through the atmosphere so that they mostly burn up in Earth's atmosphere before hitting the ground.[17] However, fuel costs for destroying a significant amount of debris with such a craft might be too costly.[18] Other ideas include attaching electro-dynamic

tethers to new satellites (see Figure 2), and fitting satellites with aero-brakes so once they reach the end of their mission they can enter Earth's atmosphere and burn up harmlessly.[19] Others are considering various ways of reducing the proliferation of orbital debris, in particular, preventing the production of orbital debris in LEO. These ideas include various international space policies, treaties, and agreements between the US and other countries that would ban tests in space that produce debris. Also, they would mandate the hardening of satellites being launched into space, so that they are not only less vulnerable to the harsh environments of space, but would significantly increase their chance of survival from a debris collision. These ideas will be discussed further in section 4.



Source: *Popular Science*, July 2008, Vol. 273, Issue 1.

Figure 2. Terminator Tethers

Section 3 – Methodology

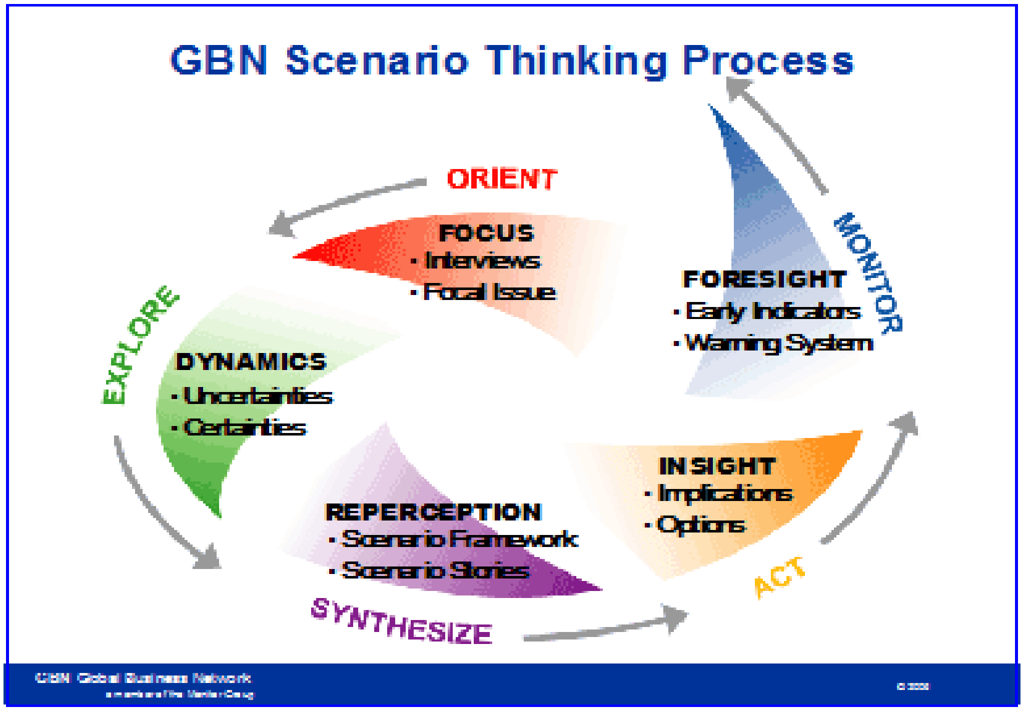
Scenarios enable new ideas about the future to take root and spread across an organization—helping to overcome the inertia and denial that can so easily make the future a dangerous place.[20]

--Eamon Kelly, CEO of GBN

Description of Scearce and Fulton's Scenario Thinking Five Phase Model

Scenarios are stories about how the future might unfold for our organizations, our issues, our nations, and even our world.[21] Scenarios are not predictions. They are stories about diverse ways in which relevant issues might evolve, such as the future political environment, social attitudes, regulation, and the strength of the economy.[22] Scenarios are designed to stretch our thinking about the opportunity and threats that the future may hold, and to weigh those opportunities and threats carefully when making both short-term and long-term strategic decisions.[23] Done well, scenarios are a medium through which great change can be envisioned and actualized.[24] Scenario thinking is a formal way to generate scenarios. It is a process through which scenarios are developed and then used to inform strategy.[25] After that process is complete, scenario thinking becomes a posture toward the world, a way of thinking about and managing change, and a way of exploring the future so they might be better prepared.[26]

A scenario-based methodology will be used to examine this thesis and will be guided by the scenario-thinking approach described by: *What If? The Art of Scenario Thinking for Non-profits* by Diana Scearce and Katherine Fulton of the Global Business Network (GBN). Scearce and Fulton's scenario-thinking model consists of five phases: Orient, Explore, Synthesize, Act, and Monitor (See Figure 2).



Source: *What If? The Art of Scenario Thinking for Non-profits,* 2004.

Figure 3. GBN Scenario Thinking Process

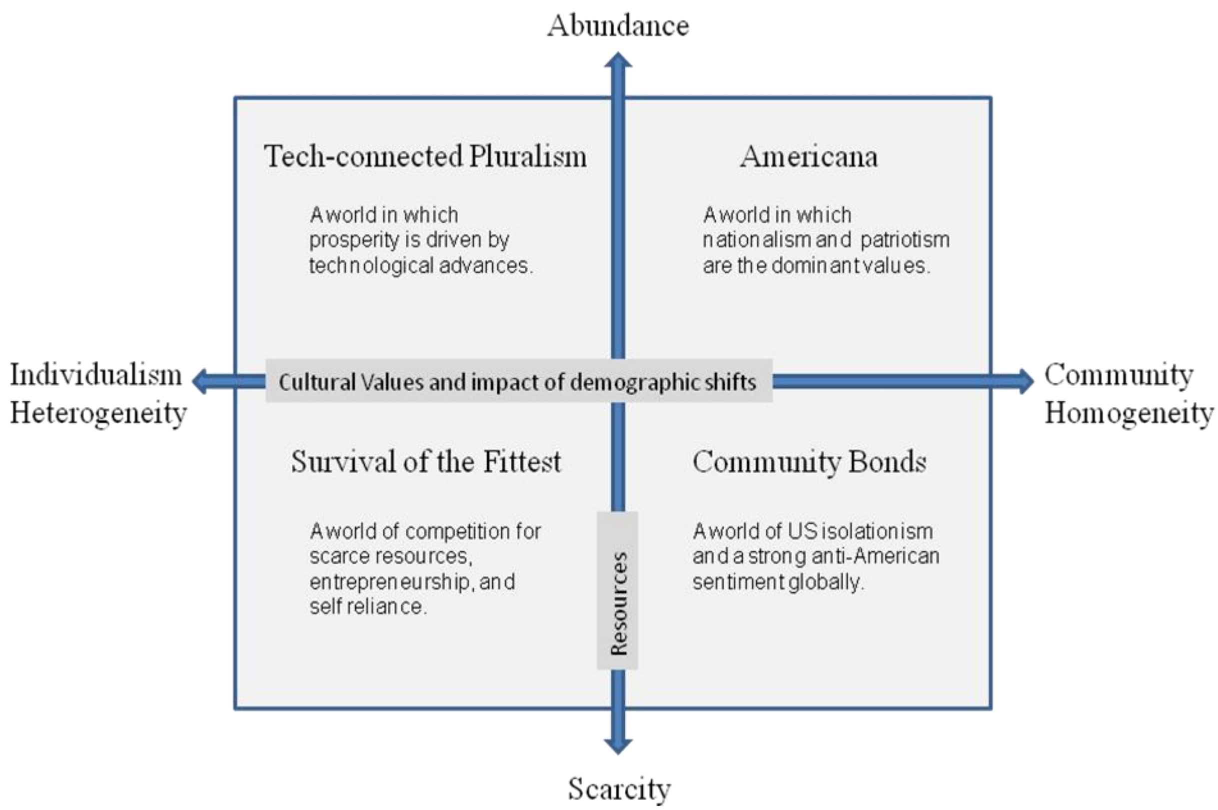
PHASE One: Orient. The Orient phase consists of clarifying the focal issue at stake, and using that issue as an orienting device throughout the remaining four phases. The process begins with learning more about the challenges that a particular organization, community, or nation faces and the underlying assumptions about the nature of those challenges and how they will play in the future.[27] Typically, the most effective way to understand these assumptions is to ask questions of key stakeholders through structured interviews. However, due to time constraints for this research paper the assumptions will be generated from a variety of books, journals, scholarly periodicals, websites, and magazines. The focal issue for this research is a catastrophic collision from orbital space debris. This phase also includes establishing a time frame for the possible futures. Most scenarios that are developed to inform strategy look five to 10 years into the future.[28] The timeframe should always reflect how rapidly the issue in question is likely to

change.[29] Currently, the volume of space debris will soon make it difficult to maneuver spacecraft without risking an accident; therefore, it will not be necessary to look too far into the future. Thus, the year of 2015 was selected for the possible futures.

PHASE Two: Explore. The Explore phase consists of the scenario thinker examining the issue in greater depth and identifying the 'driving forces' that could shape the focal issue (catastrophic collision from orbital space debris) from the orient phase. Driving forces are the forces of change outside normal control that will shape future dynamics in both predictable and unpredictable ways.[30] Driving forces include factors and shifts in the environment such as social, technological, economic, environmental, and political. Driving forces can be either pre-determined elements or uncertainties.[31] Pre-determined elements are forces of change that are relatively certain over a given future timeframe and uncertainties are unpredicted driving forces.[32] The driving forces for catastrophic collision from orbital space debris will be discussed further in section 4.

PHASE Three: Synthesize. In this phase researchers synthesize and combine the driving forces that you have identified to create scenarios.[33] Likely, individuals will have identified several driving forces however, some are not as important as others. Therefore, phase three is a narrowing phase in which one will cull and refine your driving forces to just a handful.[34] The Synthesize phase contains three elements. First, select the critical uncertainties from the driving forces that were classified by importance and degree of uncertainty. Second, construct the scenario framework using each critical uncertainty as an axis for a two-dimensional matrix, with the range of uncertainty representing the polar extremes of each axis (see Figure 4 for example). Each quadrant of the matrix will represent a possible scenario, or a potential future. Finally, create a short, distinctive, yet descriptive name for each notional future (based on the synthesis

of the two poles that comprise that quadrant) and write a brief supporting narrative. Scenarios for orbital debris will be discussed more in section 4 of this paper.



Source: *What If? The Art of Scenario Thinking for Non-profits*, 2004.

Figure 4. Example Scenario Framework

PHASE Four: Act. In phase four researchers use scenarios to inform and inspire action.[35] The Act phase consists of developing scenario implications and a strategic agenda. After the scenarios have been developed one must imagine them self living in each one. One must ask themselves what they would do to prepare if the scenario is the future. One must also ask themselves what actions they would take to avoid or mitigate a negative scenario. The answers to these questions are the scenario implications.[36] The patterns and insights that emerge from the scenario implications are the building blocks of the strategic agenda—the set of

strategic priorities that will help one make progress on the long-term goals.[37] The predetermined elements identified during the scenario development process can be used to decide if any of them figure prominently in the strategic agenda.[38]

PHASE Five: Monitor. The last phase identifies specific warning signals or other leading indicators that could forecast the emerging reality of a particular future, and then monitor for them. Leading indicators are signs of potential or significant change.[39] Leading indicators can be obvious or subtle. Leading indicators can serve as powerful signals to adapt strategy to the changing environment.[40] As leading indicators are identified, strategies can be put in place to respond to the emerging reality.[41]

Method Justification

In order to gain more insight into ideas of how to handle the debris problem, along with the driving forces and effects of debris over the next 5 years, this paper will describe four future scenarios based on consequences of orbital space debris in the year 2015. These scenarios are by no means predictions of the future. They are simply a way to analyze the challenges and potential solutions the US must consider with respect to the orbital debris dilemma to protect our vital space assets.

Section 4 – Application of Scenario Five Phase Model

Orient Phase

As mentioned earlier, the first phase of the scenario thinking process is the ORIENT PHASE consisting of clarifying the focal issue at stake, and using that issue as an orienting device throughout the remaining four phases. The focal issue of the paper is a catastrophic collision from orbital space debris in the year 2015. To better understand the situation, one must characterize the issue based on the challenges, facts, and assumptions associated with orbital space debris. The challenges are that launching of satellites and the subsequent abandonment at end-of-life has been a major contributor to the growth of orbital debris in LEO. However, explosions of satellites (either by accident or by design) have also made a significant contribution to the current orbital debris situation. The fact of the matter is that orbital debris concerns have captured the attention of nations worldwide. Thus, there are several international programs studying orbital debris through testing and modeling of space asset impacts and the debris environment. This has led to cooperation in the study of space debris through both the Inter-agency Space Coordination Committee (IADC) and the United Nations.[42] Studies have shown that orbital debris in LEO continues to grow at a rate of approximately 5 percent annually.[43] An assumption can be made based on these studies that at that rate LEO will be so saturated with debris in the near future the threat to space assets will be overwhelming. One such study that shows this alarming trend is the National Aeronautics and Space Administration (NASA) long term debris environment model called LEGEND. The LEGEND model takes into account projected future launch traffic based on historical data and sources of debris. The sources of debris include spent upper stages and spacecraft, mission related debris (MRD) released during spacecraft deployment or operations, explosion and collision fragments, and

sodium potassium (NaK) droplets that have been tracked since the 1990's (caused by a Soviet space vehicle nuclear reactor ejections through the 1980's).[44] The model also uses the industry standard Monte Carlo simulation method due to the statistical nature of future collision events. Table 3 below shows all the parameters used in the study which looked out to the year 2035.

Table 2 LEGEND parameters used in the current study

Parameter	Value
Region of space studied	LEO (200 km altitude through 2000 km altitude)
Study period	1957 through 2035 (79 years)
Debris sources included	Operational and spent payloads and rocket bodies MRD Fragments (explosions and collisions) Sodium potassium droplets (NaK) treated as solid
Debris sources excluded	Solid rocket motor slag (Al_2O_3) Ejecta and paint flakes
Traffic cycle for projection	1999 through 2006 (8 years) cycled through 2035
Constellation spacecraft, upper stages, MRD	Inserted in orbital during in historical period. Inserted in orbit during projection period through 2019, via the traffic cycle. Orbcomm stationkeeping 'off' at end-of-mission Iridium perigee lowered to 225 km at end-of-mission Globalstar re-orbited to 1515 × 1515 km orbit
Solar flux cycle for projection	Repeated 11-year cycle based on curve fit of historical daily measured flux [**53**]
Excluded objects in launch file	Space Shuttle, International Space Station, progress vehicle, mission-related debris associated with these crewed vehicles
Operational spacecraft definition	Constellation spacecraft ($\leqslant$8 years in orbit) Non-constellation spacecraft ($\leqslant$5 years in orbit)
Mitigation measures applied	Standard LEGEND future explosion rate based on recent past activity Collisional avoidance among operational constellation members The 25-year guideline not explicitly applied
Monte Carlo iterations within study period	200

Source: *Journal of Aerospace Engineering*, Dec 2007, Vol. 221 Issue 6.

Table 3. LEGEND Parameters

Some interesting assumptions can be made about the future of orbital debris based on the results of LEGEND (see Table 4). First, collisions between objects larger than 10 centimeters (cm) will increase from the current average of approximately 1.4 times per year to an average rate of 5.3

times per year by 2035, which is an increase of about 9.5 percent per year. Second, "collisions between small objects (<10 cm) and large objects (>10 cm) average nearly 95 percent of all events."[45] Of those events about 98 percent were non-catastrophic.[46] Based on the modeling evidence it seems to present an argument that "the statistics for catastrophic collision events are low in the historical period."[47] However, the catastrophic collision events begin to increase by the end of the study period and by then an average of 5 percent of all collision events are catastrophic.[48] Regardless, the chance of one potential catastrophic event should be a cause for concern. Furthermore, "even a non-catastrophic impact on an operational spacecraft could compromise a mission."[49]

Time period	Historical period 1957–2006 (50 years)	Total period 1957–2035 (79 years)
Average number of collisions by impactor/target size		
Target ⩾ 10 cm, Impactor ⩾ 10 cm	1.4	5.3
Target ⩾ 10 cm, Impactor < 10 cm	27.7	109.5
Target < 10 cm, Impactor < 10 cm	0.3	1.3
Average number of collisions (All)	29.4 (+5.1)	116.1 (+35.1)
Catastrophic	1.6 (+2.2)	6.6 (+7.6)
Average number of collisions (both objects ⩾ 10 cm)	1.4 (+1.2)	5.3 (+2.8)
Catastrophic	0.9 (+1.0)	3.3 (+2.0)
Average number of collisions (Target ⩾ 10 cm, Impactor < 10 cm)	27.7 (+4.9)	109.5 (+32.3)
Catastrophic	0.5 (+0.7)	2.0 (+1.7)
Average number of collisions (Non-constellation operational S/C)	1.9 (+1.4)	4.7 (+2.4)
Catastrophic	0.1 (+0.4)	0.3 (+0.5)
Average number of collisions (Constellation operational S/C)	0.5 (+0.7)	0.9 (+0.9)
Catastrophic	0.1 (+0.2)	0.1 (+0.3)
Average number of collisions (NaK)	4.5 (+1.9)	12.22 (+3.30)
Catastrophic	0.2 (+0.4)	0.32 (+0.55)
Average number of non-catastrophic collisions (Target ⩾ 10 cm, Impactor < 10 cm)	27.2 (+4.9)	107.5 (+31.4)
Target is intact (upper stage, spacecraft, MRD)	25.2 (+4.7)	95.6 (+25.1)
Target is operational S/C	2.0 (+1.5)	5.2 (+2.6)

Source: *Journal of Aerospace Engineering*, Dec 2007, Vol. 221 Issue 6.

Table 4. LEGEND Results—Average Collision Events

Explore Phase

Now that the stage has been set examination of the issue of catastrophic collision of orbital debris in greater depth and determination of the driving forces over the next five years can begin. As mentioned in section 2 these forces can be either pre-determined elements or uncertainties.

The pre-determined elements (relative certainties in the future) of orbital debris are that: (1) launches will continue to occur worldwide adding to the debris problem and; (2) current international space law will remain in effect for the foreseeable future.

Currently, the United States is the undisputed leader in space operations averaging approximately 30 launches per year.[50] Even with the recent announcements of cutbacks in manned missions, the "US will continue to launch assets in space at its current pace in order to replace or upgrade aging satellites due to the US's growing reliance on space assets in LEO for ocean reconnaissance, weather forecasting, communications, and ground imaging."[51] Russia, the world's second space power is putting satellites into space at an impressive rate averaging more than 25 launches per year and is expected to continue at this rate for the near future.[52] Countries such as China (averaging six launches per year), Japan (averaging one to two launches per year), and the European Space Agency (averaging 10 launches per year) are expected to maintain or slightly increase their launch rates.[53] While other active space programs in countries such as Canada, India, Israel, Thailand, South Korea, North Korea, Brazil, Argentina, Australia, Spain and Ukraine are expected to have a slight increase in their currently sporadic launch rates.[54]

International regulations will continue to exist and be refined for space. Current international space law relevant to orbital space debris such as the *Limited Test Ban Treaty of*

1963 will remain in effect for the near future. This treaty bans the testing of nuclear weapons in the atmosphere, in outer space, and underwater.[55] Therefore, states are not to conduct nuclear weapon tests or other nuclear explosions in outer space or assist/encourage others to conduct such tests or explosions.[56] The next space law currently in effect is the UN's *Outer Space Treaty of 1967*, which establishes basic legal principles and prohibitions related to space.[57] There are five main articles of this treaty related to orbital space debris. The first is Article IV, which states "nuclear weapons and other weapons of mass destruction may not be placed in orbit, installed on celestial bodies, or stationed in space in any other manner."[58] The second is Article VI, which says that states are responsible for all governmental and private space activities and is required to supervise and regulate private activities.[59] The third is Article VII, which says that states are internationally liable for damage to states (and its citizens) caused by its own space objects (including privately owned ones).[60] The fourth is Article VIII, which says that states retain jurisdiction and control over space objects in space or on celestial bodies.[61] The fifth and final article is Article IX, which says that states are required to conduct international consultations before proceeding with activities that would cause potentially harmful interference with activities of other parties.[62] This article also says that states must carry out their own use and exploration of space in a way as to avoid harmful contamination of outer space, the moon, and other celestial bodies, as well avoiding the introduction of extraterrestrial matter that could adversely affect the environment of the earth.[63] Another treaty that is related to orbital space debris is the *Antiballistic Missile (ABM) Treaty* between the United States and USSR of 1972. This treaty prohibits the development, testing, or deployment of space-based ABM systems or its components.[64] The next space law applicable to orbital space debris is the *Liability Convention of 1972*. This states that a launching state is liable for damage by its space object to people and

property on earth, its atmosphere, or to another state's space object.[65] The last space law that is applicable to orbital space debris is the *Convention on Registration of 1974*. This requires a party to maintain a registry of all objects launched into Earth orbit or beyond and that the information on orbital parameters and general function of the object must be furnished to the UN as soon as practical.[66]

There are numerous uncertainties (unpredictable forces) in store for the world over the next five years. The main ones of orbital debris are: (1) technology; (2) exploitation of space vulnerabilities via cyberspace; (3) economic developments; and (4) natural disasters.

Currently, the configuration of global space technologies and assets is highly desirable from a US perspective.[67] The US has begun to rely heavily on space assets for a myriad of capabilities in recent years. Some have voiced worries that the United States will lose its lead as the global innovator in technology or that an enemy could make technological leaps that would give it significant advantages.[68] That is possible, but by no means a foregone conclusion.[69] However one thing is clear, "technology will proliferate."[70] Space technology has become increasingly available to any country or multinational corporation with the ability to fund the research or acquire the technology and place it in orbit.[71] The increasing proliferation of launch and satellite capabilities, as well as the development of anti-satellite capabilities has begun to level the playing field.[72] Adversary technological advances in kinetic-energy weapons causing structural damage by impacting the target with one or more high-speed masses, directed-energy weapons that are either ground- or air-based systems never getting close to their target, and nuclear weapons that detonate at an empty point in space could put our space assets at risk in the near future.[73] Kinetic-energy weapons such as China's 11 January 2007 successful test of a direct-ascent, kinetic-kill anti-satellite (ASAT) vehicle destroying an inactive Chinese weather

satellite generating thousands of pieces of space debris that threatened many operational spacecraft is of growing concern.[74] Another kinetic energy weapon that is of concern is microsatellites (microsats). Currently, at least 40 countries have demonstrated some ability to design, build, launch, and operate microsats.[75] Microsats can maneuver in such a way to observe and disrupt operations of orbiting assets. These microsats may soon be capable of harassing or destroying larger satellites at virtually any altitude.[76] Because these satellites are so small, they may not be easily detectable as part of a payload or when maneuvering in space. Directed-energy weapons are laser, radio frequency, and particle beam weapons. Lasers operate by delivering energy onto the surface of the target and gradual or rapid absorption of this energy leads to several forms of thermal damage.[77] Radio frequency (RF) weapons such as the high-power microwave (HPM) have either ground-and space-based RF emitters that fire an intense burst of radio energy at a satellite, disabling electronic components.[78] Nuclear weapons are perhaps the technology of most concern to US space assets. Some argue though that adversaries would desist from using nuclear weapons in space out of fear of retaliation.[79] While others say "what better way to use nuclear weapons than to destroy a key military capability of an enemy country without killing any of its population."[80] Regardless of the arguments, one thing is clear; a nuclear detonation would have three huge environmental effects in space: electromagnetic pulse (EMP), transient nuclear radiation, and thermal radiation.[81] EMP from a nuclear detonation will induce potentially damaging voltages and currents in unprotected electronic circuits and components virtually rendering space assets inoperative.[82] Increased radiation from such a detonation would also have profound effects on the space environment. This would severely damage nearby orbiting satellites reducing the lifetime of satellites in LEO from years to months or less and make satellite operations futile for many months.[83] The risk of this

potential threat is significant. To execute this mission, all that is needed is a rocket and a simple nuclear device.[84] Countries such as Iran, North Korea, Iraq, and Pakistan possess such missiles that could carry warheads to the necessary altitudes to perform such missions.[85] Technological advances in adversary weaponry are certainly hard to predict even in the near term. However, if this weaponry matures enough and is successfully used it will create additional space debris from the orbiting satellites being rendered inoperative (space junk) and becoming potential hazards to other satellites.

Another unpredictable driving force that needs to be considered is adversary exploitation of space vulnerabilities via the cyber domain. Through cyberspace, enemies (both state and non-state actors) will target industry, academia, government, as well as the military in the air, land, maritime, and space domains.[86] One of the easiest ways to disrupt, deny, degrade, or destroy the utility of space assets is to attack or sabotage the associated ground segments through cyberspace.[87] The ground segment includes telemetry, tracking, and commanding of space assets and space-launch functions. Ground stations are an extremely critical piece of a satellites continued operation. However, many satellite tracking and control stations are lightly guarded and many satellite communications, launch, data reception, and control facilities are described in numerous open-source materials making the ground segment extremely vulnerable to cyber attack.[88] An attack on a fixed ground facility can stop data transmission, render launch facilities unusable, and prevent control of satellites.[89] Thus, rendering affected orbiting satellites inoperative from the communication disruption and creating a risk to other active satellites and a potential for additional orbital debris. A single incident or a small number of incidents could significantly impact space systems for years.[90]

The next unpredictable driving force that needs to be considered is economic developments. The recent economic downturn has certainly been felt worldwide. Nevertheless, the US dollar is still the primary unit of international trade, allowing the US to borrow at relatively low rates of interest.[91] However, the increased trend of US borrowing creates uncertainty about the ability of the US to repay the ever growing debt and the future of the US dollar.[92] Plus, any stop in lending would push the dollar down and drive inflation and interest rates up.[93] This dynamic could encourage the establishment of new reserve currencies as global economic actors search for alternatives to the dollar.[94] These changes in global economic conditions could have important implications for global security. It could decrease the US's purchasing power and ability to allocate resources especially for defense purposes causing power shifts around the world that could adversely affect global stability. Considering these economic challenges and the relative high cost of launching satellites, this could impact requests for space services worldwide and potentially slow the rate of newly generated orbital debris.

The last unpredictable driving force that needs to be considered is natural disasters. If large scale hurricanes, tornadoes, earthquakes or other natural disasters were to occur in the US, particularly when the nation's economy is in a fragile state and US military bases or key civilian infrastructure are affected, it could adversely impact US security.[95] Areas of the US where the potential is great to suffer large-scale effects from these natural disasters are the hurricane-prone areas of the Gulf and Atlantic coasts, and the earthquake zones on the west coast.[96] These two areas also happen to be the same location where the majority of US space launches occur at Vandenberg AFB, CA and Cape Canaveral AFS, FL. If a disaster were to occur in these two areas it could force the US to have to rely on other countries to provide launch services. Also, if any of these natural disasters were to occur at any of the satellite tracking and control stations

located throughout the world, it would disrupt communications with active satellites forcing the US to switch to an alternate station. However, due to the loss of control of the satellite other space assets in close proximity could be at risk of a potential collision with that satellite.

Synthesize Phase

As mentioned in section 3, now that the driving forces have been identified, one must combine these driving forces to create scenarios. From the critical uncertainties one must choose which two driving forces are the most important and most uncertain to the focal issue of a catastrophic collision from orbital space debris in the year 2015. These two driving forces are technology and future conflicts. These critical uncertainties are placed on two separate axes called "axes of extremes representing a continuum of possibilities ranging between two extremes."[97] Then these two axes are crossed to create a rough scenario framework, which one can use to explore the four possible scenarios for the future.[98] Each quadrant of the matrix will represent a possible scenario, or a potential future.

The next step is to create a short, distinctive, yet descriptive name for each notional future and provide a brief scenario narrative for each. The four future scenarios are: (1) Enemy of Mine; (2) Space Pearl Harbor; (3) Eyes Wide Shut; and (4) Lost In Space in the year 2015 (see Figure 5 for complete scenario framework).

The first scenario, "Enemy of Mine" is an adversary deliberate attack on space assets using kinetic or directed energy weapons. This scenario is driven by an adversary's advanced technical ability to launch an ASAT or a microsat (such as a space mine) into space to destroy or disable a satellite. It is also driven by an adversary's advanced ability to use a ground or air based system from a distance (such as a laser) to disable a satellite. It is also believed that if an adversary is willing to use these weapons in a sneak attack and wants to remain somewhat

hidden, there is a high probably that they would also be willing to conduct other attacks such as cyber in the same way. In this scenario, the use of these weapons renders the targeted satellites inoperative making it another piece of orbital debris putting other operational satellites at risk.

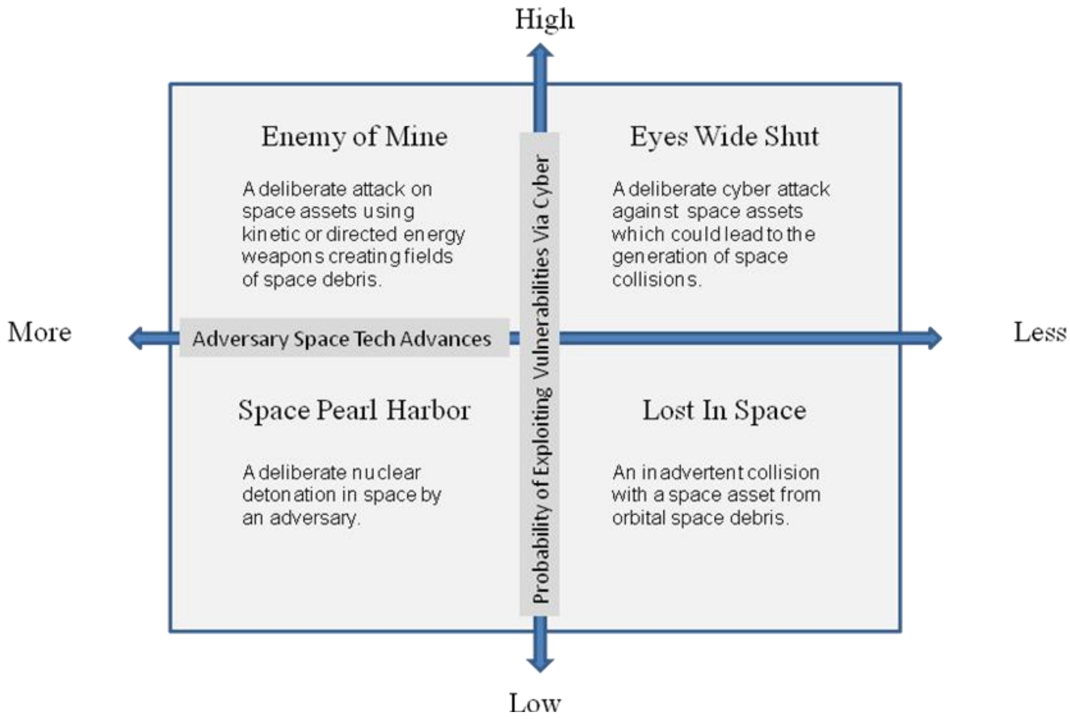
The second scenario, “Space Pearl Harbor” is a deliberate nuclear detonation in space by an adversary (such as North Korea or Iran). This type of future is driven by the adversary’s technical ability to possess a nuclear weapon, a missile to carry it, and ability to remotely detonate the device. Even though several countries already possess these capabilities independently, it would still require technological advances in systems engineering to pull all the capabilities together to be successful. This scenario would not only wipe out nearby satellites from the blast and radiation, but create huge amounts of additional orbital debris increasing the likelihood of catastrophic collisions with other space assets. Given that the US has numerous nuclear detection satellites orbiting the earth, the location of the adversary would likely be readily identified before satellites were rendered inoperative. Therefore, considering an adversary would be willing to launch an attack of such magnitude, this adversary is suspected to not be worried about conducting sneak attacks and unlikely to wage a cyber attack.

The third scenario, “Eyes Wide Shut” involves a deliberate cyber attack by an adversary against space assets, specifically ground stations. This scenario is driven by an adversary’s high probability to conduct cyber attacks. Because many countries have developed these types of capabilities, it would not require any space technology advances in order to conduct such an attack. Some countries even have “hackers that routinely probe DOD networks and computers.”[99] In this scenario, communication to satellites and data transmission from the satellites to the ground stations is completely severed. Without the communication link, satellite

control is lost and the satellites become large masses of hurling orbital debris putting other satellites at risk of a collision.

The fourth scenario, "Lost in Space" is an inadvertent collision of a space asset with one of the thousands of pieces of existing orbital debris. This scenario is very real and because it is attributed to the current debris situation, it isn't driven by either adversary technological advances or probability of conducting cyber attacks. There have been several documented space junk near misses with the ISS and in each instance the ISS was maneuvered out of harms' way to avoid the objects. However, in this scenario it isn't a near miss, it's a direct hit. A small piece of debris (no more than 20 millimeters in diameter) is detected too late to instruct the ISS to take evasive measures to avoid it. The debris, traveling at about 10 times the speed of a rifle bullet, strikes the ISS creating a massive hole in the huge structure. The collision is so severe that it knocks out the on-board communication and life support system and the ISS is sent tumbling out of control. The ISS and crew are

lost.



Source: *What If? The Art of Scenario Thinking for Non-profits*, 2004.

Figure 5. Complete Scenario Framework

Act Phase

Now that the four scenarios have been developed and briefly described, one must identify the scenario implications and a strategic agenda (set of priorities to help make progress on long-term goals). So what would it be like living in one of these scenarios? Is there anything one could do to avoid or mitigate these scenarios for the future? The answers to the first question will identify scenario implications in the areas of global communications, the economy, safety, and US national security. The answers to the second question will identify a strategic agenda in order to mitigate the orbital debris problem.

So what would it be like living in any of these scenarios? The world has become increasingly reliant on satellites to provide information such as communications, internet access,

navigation, military surveillance, environmental research, and banking. A loss of one or several satellites that provide these services from a deliberate act by an adversary could affect nearly everyone on the entire planet, especially if it was a nuclear detonation in space. The first implication is the disruption of global communications. People would not be able to communicate via cell phones or the internet. The world banking industry would literally shut down crippling an already fragile economy. US and coalition military forces around the world would not have the ability to use space assets for surveillance and GPS navigation to track friendly forces or targeting/destroying enemy forces leaving US and coalition forces vulnerable to attack and potential fratricide. In fact, a similar type of situation on a much smaller scale has already occurred in the past when a single satellite, Galaxy IV, lost its bearing in 1998.[100] Forty-five million people, including hospital personnel, were disconnected from their paging service.[101] Also, local affiliates such as the National Public Radio ceased broadcasting, Reuters was unable to send wire stories to media outlets, and Chinese Television Network couldn't transmit any of their news feeds.[102] ATMs experienced service interruptions, as did credit card systems at gas stations and grocery stores.[103] A second implication deals with world safety. As in the scenario, Lost in Space, the loss of not only a costly space asset (the ISS), but the death of an international crew would be devastating to all countries affected. As mentioned earlier, this particular incident is very real. In fact, the preliminary results of a recent NASA risk assessment of the soon to be decommissioned Space Shuttle puts the risk of a manned spaceflight mission into perspective. The study concluded that "space debris accounts for 11 out of 20 of the most likely scenarios that could lead to the loss of another shuttle."[104] Another safety issue that is of concern, which could be the result of any of the four stated scenarios, is the reentry of space debris into our atmosphere and possible impact on earth. Over the years, the world has been very fortunate to not have any

major incidences primarily due to the fact that large amounts of debris burn up harmlessly in the earth's atmosphere before impact. However, the possibility still remains, especially with the growing amount of debris in LEO. The third implication is the effect to US national security. Imagine the potential ramifications from scenarios Enemy of Mine or Eyes Wide Shut "if space debris destroyed an early-warning satellite of an adversary nuclear-armed nation."[105] The US may not get any advanced warning of a launched nuclear attack against the US or its allies.

So what strategic agenda should be prescribed to avoid or mitigate the possible scenarios for the future and implications from orbital debris? Author Michael O'Hanlon offers up some very good suggestions. These include: (1) hardening and defending US satellites; (2) improving space monitoring; and (3) backup/alternatives to satellite capabilities. In addition to these strategies, the US must continue to work with other countries to come up with solutions for clearing and reducing the proliferation of orbital debris.

First, hardening and defending US satellites would "require the continued hardening against nuclear effects, and where practical, more satellites should employ radio transmission frequencies and signal strengths capable of penetrating a nuclear disturbed atmosphere."[106] These measures would ensure at least minimum levels of bandwidth even shortly after a nuclear attack.[107] LEO satellites should also have sensors capable of detecting laser illuminations and possibly other attack mechanisms, as well as the means to protect themselves temporarily against such attacks through shutter controls that would shield their optics.[108]

Second, improved space monitoring would allow the US "to know if its satellites are under attack or likely soon to be under attack."[109] Sensors could trigger the deployment of shields or other protective measures against certain types of threats, such as lasers.[110] They

could also allow for ways in which a satellite identifies approaching microsats in order to maneuver away from a kinetic or explosive attack.[111]

Third, backup satellite capabilities would allow the US to have “some additional satellite capability in its inventory at all times, together with the ability to launch and make operational such satellites quickly to mitigate vulnerabilities to ASAT weapons.”[112] Also, alternative satellite capabilities especially from a military standpoint would certainly be a good idea as well. Numerous airborne assets, such as for imaging, signals intelligence, targeting, guidance, and communications, should be part of the force inventory.[113] Fiber-optic lines and undersea lines should be retained in many regions of the world to permit high-volume intercontinental communications even if satellites are lost.[114] Naval fleets, ground-force units, and aircraft should retain the ability to communicate internally through line-of-sight and airborne techniques, so they can function as single entities if satellites are disrupted.[115]

Lastly, the US must continue partnering with other countries to implement solutions to reduce and prevent orbital debris. As previously mentioned in section 2, there are several potential ideas such as using robotic trash collectors or attaching electro-dynamic tethers to new satellites, so once they reach the end of their mission they can be sent into Earth’s atmosphere to burn up. In fact, a new UK technology to clear clouds of debris in LEO was just introduced to the world on 26 March 2010. Scientists have designed and engineered a 3 kg miniature satellite fitted with a solar sail.[116] CubeSail, as it is called, is a device that can be fitted to satellites or launch vehicles being sent into orbit and can be deployed to de-orbit assets at the end of their mission.[117] If all goes well, it is believed that CubeSail will be ready for new satellites by 2011. Also, more space policies, treaties, and agreements must be reached between the US and other countries to ban tests in space that produce debris and to mandate the hardening of satellites

being launched into space. Recent international cooperation has shown some very promising steps toward making this a reality. The formation of the IADC between the US, European Space Agency, National Space Development Agency of Japan, the Russian Federal Space Agency, and space agencies from Britain, France, India, Germany, Italy, and the Ukraine have certainly promoted an awareness of the orbital debris problem. This group began making presentations to the UN Committee on the Peaceful Uses of Outer Space (COPUOS) back in 1997.[118] Several technical debris mitigation guidelines were submitted to COPUOS in 2002 and officially endorsed by the UN General Assembly back in 2007.[119] However, the endorsement wasn't legally binding, so implementation of debris-mitigation guidelines still lies in the hands of the different nation governments.[120] Therefore, there is much work yet to be done in this area.

Monitor Phase

Now one must identify the specific warning signals or other leading indicators that could forecast if a future scenario is about to unfold. Unfortunately, the warning signs and leading indicators for a potential catastrophic collision between orbital debris and space assets are already upon us. The numerous recorded debris collision incidences coupled with the expected increase in future launch rates is very alarming. Also, the increasing availability of space technology to adversary countries and rise in cyber conflicts coupled with the current vulnerabilities of the US space assets could be a recipe for a catastrophe within the next five years. China's successful ASAT test in 2007 and the ISS near miss collision with debris in 2009 are certainly two big wake-up calls to the world that the time is now to do something about the orbital debris situation.

Section 5 – Conclusion

Summary

The warning signs and leading indicators for a catastrophic collision between orbital debris and satellites or manned spaceflight missions are all around us. If significant strides are not made within the next 5 years to clear and remove orbital debris it could result in the loss of satellites and the death of space crew. Furthermore, if something isn't done to better protect space assets now it could lead to adversaries exploiting vulnerabilities through various kinetic, nuclear, and cyber attacks causing satellites to become inoperative. This would lead to the generation of new debris which will further compound the orbital debris problem. The effects of this would be felt worldwide with the disruption of communications, internet access, navigation, military surveillance, environmental research, and the banking industry. The best way to avoid

these consequences is to continue to harden satellites, improve space monitoring, and develop backups/alternatives to satellite capabilities. As mentioned, the US must also continue to partner with other countries to implement solutions of clearing and reducing the proliferation of orbital debris. The world can change the potential alarming future of a catastrophic collision from orbital debris, but the time to act is now.

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[1] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 30.
[2] Ibid, 69.
[3] Ibid, 42.
[4] Liou, J.-C. and Johnson, N.L. *Risks in Space from Orbiting Debris,* 340.
[5] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 42.
[6] Robson, David. *Calling Occupants of Interplanetary Craft, Danger Ahead,* 24.
[7] Ibid, 24.
[8] Ibid, 24.
[9] Ibid, 24.
[10] Ibid, 24.
[11] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 42.
[12] Ibid, 24.
[13] Ibid, 24.
[14] Malik, Tario. *Debris Scare Sends Station Crew Into Soyuz, 12.*
[15] Krisko, P.H. *The Predicted Growth of the Low-Earth Orbit Space Debris Environment – An Assessment of Future Risk for Spacecraft,* 983-984.
[16] Robson, David. *Calling Occupants of Interplanetary Craft, Danger Ahead,* 24.
[17] Than, Ker. *Orbital Cleanup,* 30.
[18] Ibid, 30.
[19] Ibid, 30.
[20] Scearce, Diana, and Katherine Fulton. *What If? The Art of Scenario Thinking for Non-profits,* 6.
[21] Ibid, 7.
[22] Ibid, 7.
[23] Ibid, 7.
[24] Ibid, 7.
[25] Ibid, 8.
[26] Ibid, 8.
[27] Ibid, 24.
[28] Ibid, 25.
[29] Ibid, 25.
[30] Ibid, 27.
[31] Ibid, 27.
[32] Ibid, 27.
[33] Ibid, 27.
[34] Ibid, 27.
[35] Ibid, 30.
[36] Ibid, 30.
[37] Ibid, 31.
[38] Ibid, 31.
[39] Ibid, 33.
[40] Ibid, 33.
[41] Ibid, 33.

[42] Krisko, P.H. *The Predicted Growth of the Low-Earth Orbit Space Debris Environment – An Assessment of Future Risk for Spacecraft,* 975.
[43] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 42.
[44] Krisko, P.H. *The Predicted Growth of the Low-Earth Orbit Space Debris Environment – An Assessment of Future Risk for Spacecraft,* 976.
[45] Ibid, 981.
[46] Ibid, 981.
[47] Ibid, 982.
[48] Ibid, 982.
[49] Ibid, 983.
[50] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 53.
[51] Ibid, 51.
[52] Ibid, 53.
[53] Ibid, 54-57.
[54] Ibid, 57-58.
[55] Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, 57.
[56] Ibid, 57.
[57] Frey, Adam E. *Defense of Space Assets, a Legal Perspective*, 76.
[58] Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, 57.
[59] Ibid, 57.
[60] Ibid, 57.
[61] Ibid, 57.
[62] Ibid, 57.
[63] Ibid, 57.
[64] Ibid, 58.
[65] Ibid, 58.
[66] Ibid, 58.
[67] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 62.
[68] United States Joint Forces Command. *The JOE 2010 Joint Operating Environment*, 54.
[69] Ibid, 54.
[70] Ibid, 55.
[71] Ibid, 36.
[72] Ibid, 36.
[73] Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, 276-279.
[74] Ibid, 276-277.
[75] Ibid, 277.
[76] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 65.
[77] Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, 277.
[78] Ibid, 278.
[79] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 67.
[80] Ibid, 67.
[81] Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, 279.
[82] Ibid, 280.
[83] Ibid, 280.
[84] Ibid, 280.
[85] Ibid, 280.
[86] United States Joint Forces Command. *The JOE 2010 Joint Operating Environment*, 36.
[87] Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, 273.
[88] Ibid, 274.
[89] Ibid, 274.
[90] Ibid, 274.
[91] United States Joint Forces Command. *The JOE 2010 Joint Operating Environment*, 19.
[92] Ibid, 19.

[93] Ibid, 19.
[94] Ibid, 20.
[95] Ibid, 33.
[96] Ibid, 33.
[97] Scearce, Diana, and Katherine Fulton. *What If? The Art of Scenario Thinking for Non-profits,* 28.
[98] Ibid, 28.
[99] Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, 274.
[100] David, Leonard, *The Clutter Above*, 33.
[101] Ibid, 33.
[102] Ibid, 33.
[103] Ibid, 33-34.
[104] Ibid, 33.
[105] Ibid, 34.
[106] O'Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*, 123.
[107] Ibid, 123.
[108] Ibid, 123.
[109] Ibid, 124.
[110] Ibid, 124.
[111] Ibid, 124.
[112] Ibid, 128.
[113] Ibid, 129.
[114] Ibid, 129-130.
[115] Ibid, 130.
[116] Wheeler, Howard. *A Mission to Clear Dangerous Debris From Space,* 1.
[117] Ibid, 1.
[118] Black, Samuel and Butt, Yousef. *The Growing Threat of Space Debris*, 2
[119] Ibid, 2.
[120] Ibid, 2.

Bibliography

Air Command and Staff College Space Research Electives Seminars. *AU-18 Space Primer*, Maxwell AFB, AL: Air University, 2009.

Black, Samuel and Butt, Yousef. "The Growing Threat of Space Debris" *Bulletin of the Atomic Scientists*, Mar 2010, Vol. 66 Issue 2: 1-8. http://search.ebscohost.com/login.aspx?direct = true&db= aph&AN=48453277&site=ehost-live

Brearley, Andrew. "Faster Than a Speeding Bullet: Orbital Debris*." Astropolitics*, Volume 3, Issue 1, Apr 2005: 1-34. http://www.informaworld.com/smpp/section?content=a 713727953&fulltext=713240928

David, Leonard, "The Clutter Above" *Bulletin of the Atomic Scientists*, Vol. 61, Issue 4, Jul/Aug2005: 32-37. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN= 17455589&site=ehost-live

Depczuk, D. and Schonberg, W. P. "Characterizing Debris Clouds Created in Oblique Orbital Debris Particle Impact." *Journal of Aerospace Engineering*, Oct 2003, Vol. 16 Issue 4: 177-190. http://search.ebscohost.com/login.aspx?direct=true&db=mth&AN=10848628

&site=ehost-live

Frey, Adam E. “Defense of Space Assets, A Legal Perspective.” *Air and Space Journal*, Winter 2008: 75-84. http://www.airpower.maxwell.af.mil/airchronicles/apj/apj08/win08/frey .html

Hall, G.E. “Space Debris-An Insurance Perspective.” *Proceedings of the Institution of Mechanical Engineers -- Part G -- Journal of Aerospace Engineering*, Dec 2007, Vol. 221 Issue 6: 915-924. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN =27558589&site=ehost-live

Krisko, P.H. “The Predicted Growth of the Low-Earth Orbit Space Debris Environment – An Assessment of Future Risk for Spacecraft.” *Proceedings of the Institution of Mechanical Engineers -- Part G -- Journal of Aerospace Engineering*, Dec 2007, Vol. 221 Issue 6: 975-985. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=27558584 &site=ehost-live

Liou, J.-C. and Johnson, N.L. “Risks in Space from Orbiting Debris.” *Science*, 20 Jan 2006, Vol. 311 Issue 5759: 340-341. http://search.ebscohost.com/login.aspx?direct=true&db= aph&AN=19603405&site=ehost-live

Malik, Tario. “Debris Scare Sends Station Crew Into Soyuz.” *Space News*. Vol. 20, no. 11, 16 Mar. 2009: 12.

Marks, Paul. “Network-Style Attack Could Reduce the Threat from Space Debris.” *New Scientist***,** October 11, 2008. http://search.ebscohost.com/login.aspx?direct=true&db= aph&AN=45391967&site=ehost-live

McKenna, Ted. “Lost in Space: Could Space-Based Weapons Help Protect Military Satellite Capability?” *Journal of Electronic Defense*, Vol. 28, no 1, January 2005: 40. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=15721105&site=ehost -live

Mirmina, Steven A. “Reducing the Proliferation of Orbital Debris: Alternatives to a Legally Binding Instrument.” *American Journal of International Law*, Jul 2005, Vol. 99 Issue 3: 649-662. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=18665245 &site=ehost-live

Nishida, S.-I., Kawamato, S., Okawa, Y., Terui, F., and Kitamura, S. “Space Debris Removal System Using a Small Satellite.” *Acta Astronautica*. Vol. 65, no. 1-2, July-Aug. 2009: 95-102. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=40112440 &site=ehost-live

O’Hanlon, Michael E. *Neither Space Wars Nor Sanctuary, Constraining the Military Uses of Space*. Washington D.C.: Brookings Institute Press, 2004.

Reichhardt, Tony. "Satellite Smashers." *Air & Space Smithsonian*, March 2008. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=28814468&site=ehost-live

Robson, David. "Calling Occupants of Interplanetary Craft, Danger Ahead." *New Scientist*, 18 September 2008. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=35014840&site=ehost-live

Scearce, Diana, and Katherine Fulton. *What If? The Art of Scenario Thinking for Non-profits.* Emeryville, CA: Global Business Network, 2004.

Skinner, Tony. "Pentagon Urges Effort to Address Space Debris Threat." *Jane's Defence Weekly*. Vol. 46, no. 18, 6 May 2009: 7. http://search.ebscohost.com/login.aspx?direct=true&db=mth&AN=40216542&site=ehost-live

Skinner, Tony. "Spatial Awareness". *Jane's Defence Weekly*. Vol. 46, no. 29, 22 July 2009: 24. http://search.ebscohost.com/login.aspx?direct=true&db=mth&AN=43568218&site=ehost-live

Than, Ker. "Orbital Cleanup." *Popular Science*, July 2008, Vol. 273, Issue 1: 30-31. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=32440225&site=ehost-live

United States Joint Forces Command. *The JOE 2010 Joint Operating Environment*. Suffolk, VA: Joint Futures Group, Feb 2010.

Wheeler, Howard. *A Mission to Clear Dangerous Debris From Space*. Guildford, UK: University of Surrey, 2010. http://www2.surrey.ac.uk/mediacentre/press/2010/26099_a_mission_to_clear_dangerous_debris_from_space.htm

Williamson, Ray A. "The Growing Hazard of Orbiting Debris." *Science & Technology*, Fall 1991, Vol. 8 Issue 1: 77-82. http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=9111111133&site=ehost-live